

DOE/NASA/1044-8
NASA TM-81545



NASA-TM-81545 19810007912

SPECIFYING AND CALIBRATING INSTRUMENTATION FOR WIDEBAND ELECTRONIC POWER MEASUREMENTS

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APR 16 1981

December 1980

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Prepared for
**U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs**

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1044

N81-16429#

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Summary

The wideband electric power measurement related topics of electronic wattmeter calibration and specification are discussed. Tested calibration techniques are described in detail. Analytical methods used to determine the bandwidth requirements of instrumentation for switching circuit waveforms are presented and illustrated with examples from electric vehicle type applications. Analog multiplier wattmeters, digital wattmeters, and calculating digital oscilloscopes are compared. The instrumentation characteristics which are critical to accurate wideband power measurement are also described.

The major conclusions reached are:

- (1) Electronic wattmeters capable of measuring power in switching circuit applications are available.
- (2) Commercial analytical instruments can be used to determine the power bandwidth requirements.
- (3) Errors are minimized when the current and voltage channels are matched in phase shift, but the matching must include the current transducers and all signal conditioning electronics.
- (4) Calibration of wideband wattmeters using variable frequency, variable phase sine waveforms is the only NBS-traceable method available.

Introduction

The rapid improvement in power switching electronics during the past several years has generated new applications for on/off switching controllers (choppers) and dc-to-ac inverters. One important application is for dc motor drive systems such as those found in electric vehicles. As for any power source or controller, the power efficiency is a key parameter. To determine the efficiencies of a battery-speed control chopper-dc motor system, the required test instrumentation must include a means for accurate electric power measurement. Due to the action of the chopper, which switches power at rates ranging from 400 hertz to 20 kilohertz, the system generates ac power components. While the largest part of the average power delivered to the dc motor is dc, the ac components of the power can be significant at frequencies many times the fundamental chopping frequency.

Electric power measurement can be accomplished through the use of several different techniques; but those techniques applicable to accurate wideband power measurements are limited. The rapidly advancing electronics field has made it economically attractive to measure power by using voltage signals proportional to the source or load voltage and current, and then employing electronic multiplication. Devices to generate a voltage signal proportional to instantaneous current (e.g., current shunts) are therefore an important part of electric power measurement instrumentation. Once a voltage signal has been generated by the current sensor, the electrical wattmeter instrument is reduced to an electronic box which amplifies signals where needed and then multiplies instantaneous current and voltage, resulting in an instantaneous power signal. Average power can then be readily obtained by time average integration or low pass filtering.

Accuracy over a wide bandwidth and for small power factors is an important parameter of a wattmeter for switching applications. Other important characteristics are differential inputs (to reduce restrictions on shunt and voltage probe locations), sufficient range selection, and reasonable cost.

Wideband electronic wattmeters (we are referring in this report to power source wattmeters rather than rf wattmeters) and current shunts are commercially available today. The use of coaxial shunts for wideband applications is being increasingly accepted (ref. 1). Coaxial shunts are designed to sustain high peak power and current inputs in a housing which minimizes inductive effects. Although originally intended for large transient current measurement, their broad, flat frequency response and their continuous power handling capabilities are sufficient for most power switching applications. Analytical instruments are also available with which an instrumentation specialist can determine the bandwidth requirements of his power measurement.

But questions still remain in the field of wideband power measurement. How should electronic wattmeters be calibrated to ensure accurate measurements? How should current shunts be calibrated? What spectral measurements should be made in a given application to define bandwidth requirements? This report was written to aid the test engineer in answering the questions of wattmeter

calibration and bandwidth requirements by describing techniques for wattmeter calibration and by describing the analysis of wideband power measurement requirements and specifications.

To describe the power characteristics of the nonsinusoidal periodic waveforms generated by choppers and related switching systems, the Fourier series components (sine and cosine waves harmonically related to the fundamental switching frequency) of these waveforms are generally used as a mathematical tool (refs. 1 and 2). By comparing the power content of the sum of the Fourier components with the power contained in the nonsinusoidal waveforms, one can determine the required frequency bandwidth of the instrumentation used to measure power. The average power equals the summation of all terms of the form $I_i V_i \cos \theta_i$, where I_i is the rms current magnitude of the Fourier component at frequency i , V_i is the corresponding rms voltage magnitude, and θ_i is the phase angle between the I and V waveforms of frequency i . Experimental data on the harmonic content of chopper driven dc motors has been published (ref. 3). Calibration of the current shunts and electronic wattmeters used in wideband power measurements can be based on accurately known sine wave inputs over the frequencies of interest provided that the instrument to be calibrated is linear. This report describes wattmeter calibration techniques using phase-shifted sinusoidal waveforms.

Fourier series techniques for the analysis of nonsinusoidal but periodic waveforms have been used for applications involving communications systems, vibrational and stress diagnostics, and control systems. Spectrum analyzers are usually employed. These analysis techniques can also be used for wideband power measurements involving switching electronics. But since phase angle is also important, many spectrum analyzers cannot provide all of the information necessary to accurately evaluate power spectra. In this case, correlation analyzers and Fourier transform analyzers are of value, but present a higher cost. The cost of analytical equipment has perhaps been a deterrent to its use by many test engineers involved with inverter or chopper drives for machinery.

A recent report (ref. 2) mathematically analyzed the frequency components in a switching controller application. That report also analyzed errors in the measurement of average power of sinusoidal signals. This report will present some experimental data related to these analyses. Investigators (refs. 2 and 4) have also calculated errors in using sampling techniques for electrical power measurement. The use of digital oscilloscopes as analytical tools, as

discussed in this report, is subject to the errors presented.

Symbols

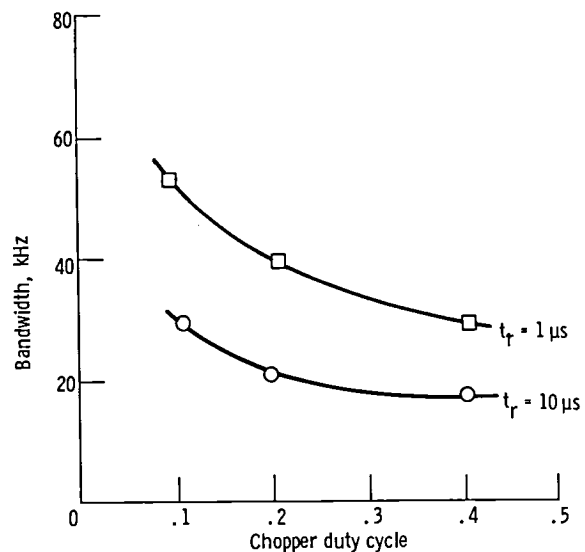
F_1, F_2	corner frequencies, Hz
f	frequency, Hz
f_1	input signal frequency, Hz
$H_1(\omega), H_2(\omega),$ $H_4(\omega)$	transfer functions in frequency domain
I_{ave}	average current magnitude
I_i	Fourier series rms coefficient of i th harmonic of current waveform, $i(t)$
I_k	complex coefficient of k th term of Fourier exponential series of periodic $i(t)$
I_p	peak current magnitude
I_{rms}	rms current magnitude
I_1	rms current magnitude at input frequency f_1
$i(t)$	instantaneous current as a function of time t
j	$\sqrt{-1}$
N	number of samples
P_{ave}	average power
$P_{XY}(\omega)$	cross-power spectrum of $x_T(t)$ and $y_T(t)$
$p(t)$	instantaneous power as a function of time t
T	time period
t	time
t_d	time delay
t_r	rise time, sec
t_s	time between samples
V_{ave}	average voltage magnitude
V_i	Fourier series rms coefficient of i th harmonic of voltage $v(t)$
V_k	complex coefficient of k th term of Fourier exponential series of periodic $v(t)$
V_o	wattmeter output voltage
$V_o'(\omega)$	multiplier output voltage in frequency domain
V_p	peak voltage magnitude
V_{rms}	rms voltage magnitude
V_1	rms voltage magnitude at frequency f_1
$V_1(\omega), V_2(\omega)$	Fourier transforms of $v_1(t), v_2(t)$

$v(t)$	instantaneous voltage as a function of time t
$X_T(f)$	Fourier transform of $x_T(t)$
x	dummy variable
$x_T(t)$	function of time for $0 \leq t \leq T$
$Y_T(f)$	Fourier transform of $y_T(t)$
$y_T(t)$	function of time for $0 \leq t \leq T$
$\delta(x)$	delta function of x
θ_i	phase angle between Fourier series terms of i th harmonic for $v(t)$ and $i(t)$
τ_a, τ_b	reciprocals of ω_a, ω_b
φ_{amp}	amplifier output phase shift
φ_1	phase angle between current and voltage at frequency f_1
ω	angular frequency, radians/sec
$\omega_a, \omega_b, \omega_c$	corner frequencies for transfer functions, radians/sec
ω_1	input frequency, radians/sec

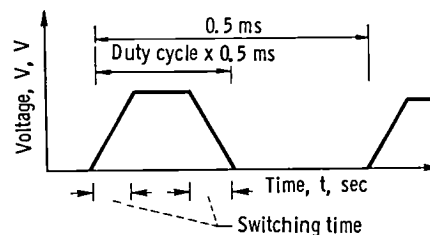
Wideband Electronic Wattmeters

The bandwidth definition of a "wideband" wattmeter, as with any instrument, will depend upon the application. A dc-to-100-kilohertz or a dc-to-1-megahertz wattmeter would be considered a "wideband" instrument for most applications involving power switching. However, the bandwidth specification of a wattmeter is usually a function of the input power factor. A commercial "20-kilohertz" wattmeter was tested with sinusoidal waveforms to be accurate to within 1 percent of full scale to 30 kilohertz with an input power factor of 1.0, but showed an error of about 5 percent of full scale at 20 kilohertz with a power factor of 0.5, indicating that its bandwidth specification was rated for resistive loads. For many applications involving inductance or capacitance, the wattmeter would exhibit errors greater than 1 percent of full scale at 10 kilohertz.

Figure 1 illustrates the bandwidth requirements for a typical application involving a switched (chopped) 2-kilohertz power system and a resistive load. The figure plots the required instrument bandwidth to measure power to within 1 percent as a function of duty cycle "on" time for two cases of state-of-the-art power switching times. The data in the figure were obtained from computer calculations wherein Fourier components of the waveform (fig. 1(b)) were summed, as frequency increased, until the total was within 1 percent of full scale of the actual power. The summation assumed an ideal low pass filter, that is, components above the cutoff frequency were disregarded completely.



(a) Required wattmeter bandwidth for resistive load power measurement to within 1 percent for 2-kilohertz chopped system, for chopper switching times of 1 and 10 microseconds.



(b) Voltage waveforms for chopped load.

Figure 1. - Chopper power measurement.

The case of a load with a reactive component would alter the bandwidth requirements due to varying impedance and phase angle with Fourier frequency.

Analog Multiplier Wattmeters

Figure 2 is the simplified block diagram of an idealized electronic wattmeter based on an analog multiplier. The input amplifiers are shown as differential amplifiers. Commercial electronic wattmeters may not have this feature. In some instances, the inputs are single-ended and are referred to the instrument chassis. In other instruments the low side of the current and voltage inputs must be tied together but this common can float off chassis ground. In this latter case, the instrument may not have been designed for wideband common mode rejection so that any significant common mode voltage at chopping frequencies can cause large errors. Again depending upon the

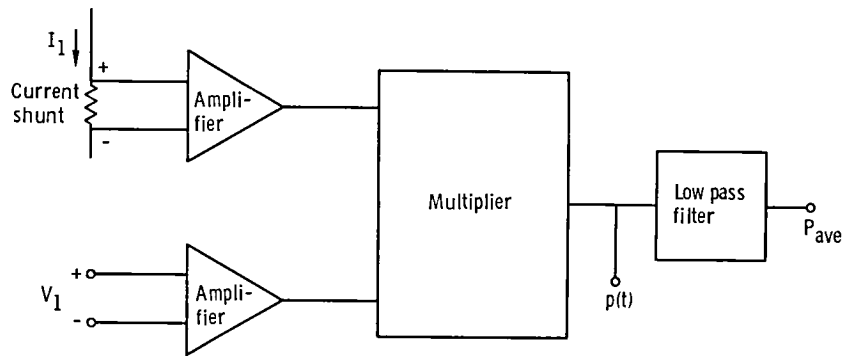


Figure 2. - Analog multiplier-based electronic wattmeter block diagram.

application, the wattmeter input configuration can be a major source of error.

Other instruments capable of wideband power measurements have their input amplifiers capacitively coupled, thereby eliminating any dc response. These types of ac power wattmeters must be used in conjunction with dc power wattmeters to measure total power where a dc component is present.

Since the current shunt voltage is typically low (tens to hundreds of mV), the current channel amplifier must have a gain of about 10 to 100 to raise the current signal amplitude to design levels for the analog multiplier circuit. The voltage amplifier is primarily an isolation amplifier, since typical voltage amplitudes are 10 to 200 volts. Unless the wattmeter has been carefully designed, the difference in amplifier function between the two channels can lead to phase errors at the amplifier outputs. In addition to the amplifiers built into wattmeters, signal conditioning amplifiers are sometimes used at the inputs to the wattmeter. Whether the amplification is internal to the wattmeter or added to the power measurement instrumentation for a special purpose, overall channel matching is important, as shown by the following data and discussion.

Amplifiers are often treated in system analyses as having first order gain characteristics referenced to a single value corner frequency. Power measurement errors have been calculated for mismatched first order input channels in a wattmeter (ref. 2). To experimentally evaluate the applicability of calculations of this type to real power measurement instrumentation, tests were made on a typical high quality wideband differential amplifier. The differential input, variable gain, variable bandwidth amplifier tested would be a possible choice for applications where current shunt placement requires a floating input.

Test data were taken on the mismatch error caused by adding the 1-megahertz bandwidth amplifier in

one channel only in a simulated power measurement, wherein generator signals were fed to a wideband wattmeter, as shown in figure 3. Data were obtained with and without the external amplifier so that the internal wattmeter mismatch effects could be corrected in determining the mismatch due to the amplifier alone.

Test data were obtained for 50-kilohertz sine wave inputs phase shifted at 0° , 60° , and 80° . At a frequency ratio (input frequency to the 1-megahertz corner frequency) of 0.05, the calculated amplifier phase shift φ_{amp} for a first order amplifier gain characteristic is 3° . This deviation from the generated phase angle translates to a calculated error in power of about 9 percent of reading at a generated phase angle of 60° and about 30 percent of reading at an angle of 80° .

Data taken with and without the differential amplifier revealed a phase shift caused by the amplifier of 5° at 50 kilohertz. The phase-shift power error for 5° is 15 and 50 percent of reading at phase angles of 60° and 80° , respectively. The amplifier output magnitude rolloff at 1 megahertz was verified to be 0.70, the expected value for a first order system. Since a 5° phase shift at 50 kilohertz for a first order system implies a -3-decibel point at 600 kilohertz, it was probable that the output characteristic of this

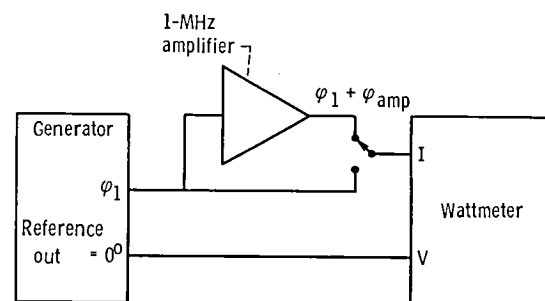


Figure 3. - Test setup for determining effects of amplifier characteristics on channel matching.

amplifier was of higher order (although no explicit phase-shift test data were taken to verify this).

The important point illustrated here is that, although the amplifier magnitude error at 50 kilohertz is below 1 percent, the phase shift-related power error was large at large phase angles. An amplifier bandwidth of 10 times data bandwidth is not always sufficient for 1 percent accuracy when phase angle shifts must be considered.

Also to be emphasized, an amplifier gain roll-off (with frequency) test may not be sufficient to allow amplifier matching if the amplifiers are of different design. Table I illustrates the calculated phase angle, for a cascade of two first order systems, at the -3-decibel magnitude frequency for selected combinations of pole frequencies that could be encountered in amplifier designs.

The x-5x entry can be used to explain the 1-megahertz amplifier data previously cited. The calculations show that in a second order system comprised of a 5-megahertz amplifier of first order followed by a first order filter with a corner at 1 megahertz, the -3 decibel magnitude roll-off point will occur at 980 kilohertz, but the phase angle φ_{amp} at 980 kilohertz will be 55.3° . Therefore, magnitudewise, the amplifier will look similar to a first order system at the -3-decibel point, but it will have excessive phase shift.

In this discussion, we are not suggesting that suitable differential amplifiers for wideband power instrumentation cannot be found, but we are again recommending careful selection and matching. Amplifier specifications for bandwidth are not sufficient information to ensure this matching.

The appendix presents a simplified wattmeter model parameter which can be experimentally determined and used to predict wattmeter accuracy as a function of frequency and power factor.

Referring again to the idealized electronic wattmeter, figure 2 shows both an instantaneous

power output p and an average power output P_{ave} . The former output is of secondary use in most applications. The average power defined by

$$\frac{1}{T} \int_0^T i(t)v(t) dt = \frac{1}{T} \int_0^T p(t) dt$$

is normally derived by filtering the multiplier output. The filter time constant must be large enough to reduce the ripple caused by the lowest frequency components of the multiplier output. This constraint must be balanced by the application requirements for response time to source or load variations. Because of the filter, there is a potential incompatibility between fast response to average power fluctuation and effective filtering of low frequency instantaneous power waveforms.

Digital Wattmeters

A digital wattmeter utilizes digital multiplication in generating power information from voltage and current inputs. (Although commercial analog multiplier wattmeters are available in which the average power output is digitized, this "digital output"-type wattmeter is not a digital wattmeter in the normally used sense.) In the wattmeter shown in figure 4, the analog voltages representing current and voltage are individually digitized at a rate many times that of the input frequencies. All instantaneous power calculations are performed digitally, either in a digital multiplier circuit or in a computer. Then average power can either be digitally calculated or can be generated as a filtered analog signal as shown in figure 4. The analog input circuits of the digital wattmeter have the same constraints as in analog multiplier wattmeters. The primary advantage of a digital wattmeter is that the system errors following digitization can approach zero. Also, the multiplication does not have to be accomplished in real time if the data samples can be stored. Thus the digital wattmeter bandwidth is limited only by the matching of the signal conditioning and the digitizing rates. Quantization error can be a disadvantage of a digital wattmeter, especially when readings significantly less than full scale are desired.

The only known commercial instrument which can qualify as a "digital wattmeter" was not designed as a wattmeter. The instrument is a calculating digital oscilloscope which can store, in a microcomputer memory, data from two input channel digitizers. Subsequent calculations can be performed to generate instantaneous power, followed by the integration necessary to give average power. The major limitations in the use of a calculating digital oscilloscope are two: (1) the front end amplifiers have single-ended inputs, (2) the power calculations

TABLE I. - CALCULATED PHASE
SHIFT FOR SECOND ORDER
SYSTEM WITH CORNER FREQUENCIES
OF F_1 AND F_2 AT -3-DECIBEL
MAGNITUDE POINT

F_1 , Hz	F_2 , Hz	F at -3 dB magnitude point), Hz	Phase angle at φ_{amp} , deg
x	∞	x	45
x	5x	0.98x	55.3
x	2x	.84x	62.6
x	1.5x	.77x	64.5
x	x	.64x	65.5

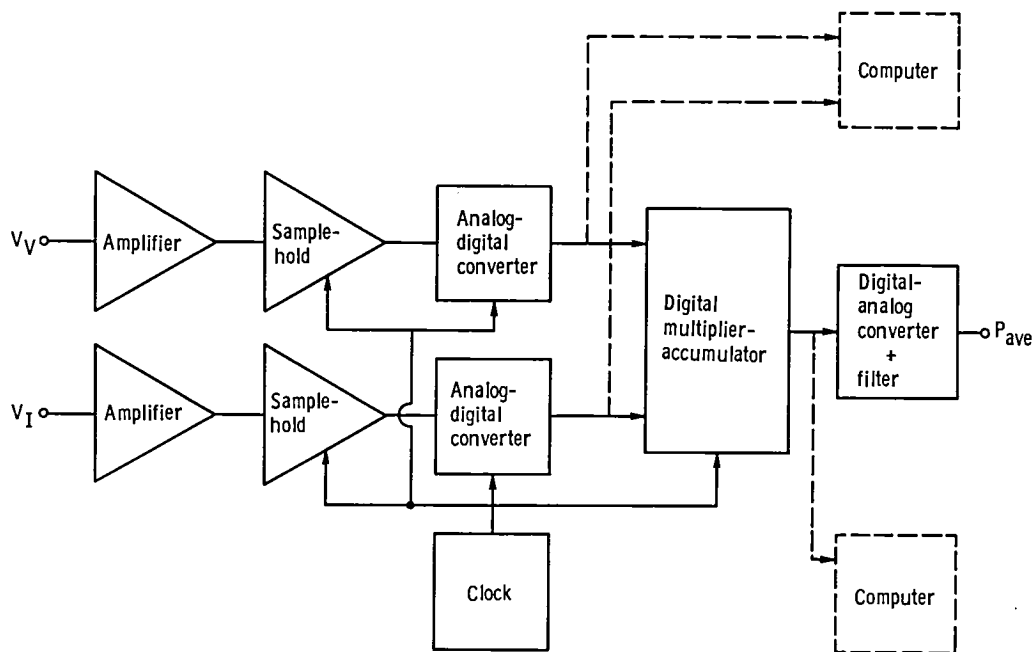


Figure 4 - Digital wattmeter block diagram.

take a significant amount of time so that a continuous power reading is not available. (Further important uses for a digital oscilloscope will be discussed in a later section.)

Comparison of Electronic Wattmeter Readings

In the previous section on digital wattmeters, the use of a digital oscilloscope as a wattmeter was discussed. We present here comparisons of power data obtained with an analog multiplier-based

electronic wattmeter and a calculating digital oscilloscope. The data were obtained with a variety of input waveforms generated by a digital phase generator. Table II is a summary of the data, showing the input characteristics and the discrepancies between the measurements of the two instruments. The maximum error shown is 0.5 percent of full scale of the analog wattmeter. These data show that electronic wattmeters are presently available that can accurately (better than 1 percent of full scale) measure wideband power for input waveforms typical of switching power sources.

TABLE II. - COMPARISON OF DIGITAL OSCILLOSCOPE AND ANALOG ELECTRONIC WATTMETER POWER MEASUREMENTS FOR VARIOUS INPUT WAVEFORMS

Waveform type	Frequency, kHz	Voltage to current phase angle, deg	Digital wattmeter		Discrepancy	
			Sampling rate, kHz	Reading, W	Percent of reading	Percent of full scale
Sine	5	0	500	13.6	1	0.1
	20	0	500	13.6	1	.2
	50	0	500	13.3	1	.1
Square	20	0	500	26.5	2	0.5
	20	45	500	14.6	3	.4
Square + dc	1	0	200	22.6	1	0.2
		45		17.3	1	.2
		90		11.5	2	.2
		180		.3	0	.0
		0	↓ 500	-17.0	.5	.1
		90		-8.6	1	.1
		90		-8.6	1	.1

Calibration Techniques

Wideband voltage multiplying wattmeters with external shunts can be easily calibrated to within 1 percent of full scale from dc to 100 kilohertz for in-phase inputs. The voltage standards and voltmeters are directly certifiable by the National Bureau of Standards (NBS). The out-of-phase calibration over the same range is limited by the range of frequency or voltage levels in currently available phase generators and is not directly NBS traceable. Although the NBS does not certify phase generators or meters, the electronic industry has accepted a phase angle standard that uses a ratio transformer certified by the NBS. Currently available phase-meters do have the required range and accuracy and can be referenced to time and frequency standards.

The calibration technique described here is used because the standards are available and the calibration method will sufficiently characterize the wattmeter response to waveforms of current interest. If known sine wave voltage levels with known phase angles are applied to the wattmeter, then the bandwidth can be determined for any phase angle. The four quadrant (0° to 360°) sine wave response accuracy will determine the limit to which harmonics of distorted waveforms can be measured. The validity of this calibration technique is based on the following factors: (1) the inputs are voltage levels, (2) the voltage levels are accurate dc or sine wave values and (3) the phase angle of the sine wave inputs can be varied throughout 0° to 360° and measured accurately at the wattmeter input.

Because of equipment limitations the calibration operation is separated into three different tests. (1) a dc response test, (2) an ac in-phase response test, and (3) an ac out-of-phase response test. Full scale accuracy, linearity and bandwidth data are taken over the complete input range in the dc and ac in-phase tests. The input voltage levels and phase angle should be monitored for each data point. The out-of-phase test is run separately because the available phase angle generators do not have the complete output capabilities desired for full scale accuracy and linearity data.

System connections for performing the above tests are shown in figure 5 for a wattmeter with single-ended inputs. At high frequencies some phase shift will occur through the voltage divider in the in-phase test; however, the amount of error can be calculated from the phase angle and input level readings. The data can then be corrected, but in most cases the error will be insignificant.

Data from the preceding tests can now be plotted to show the wattmeter characteristics as shown in the examples in figures 6 and 7. The phase angle data

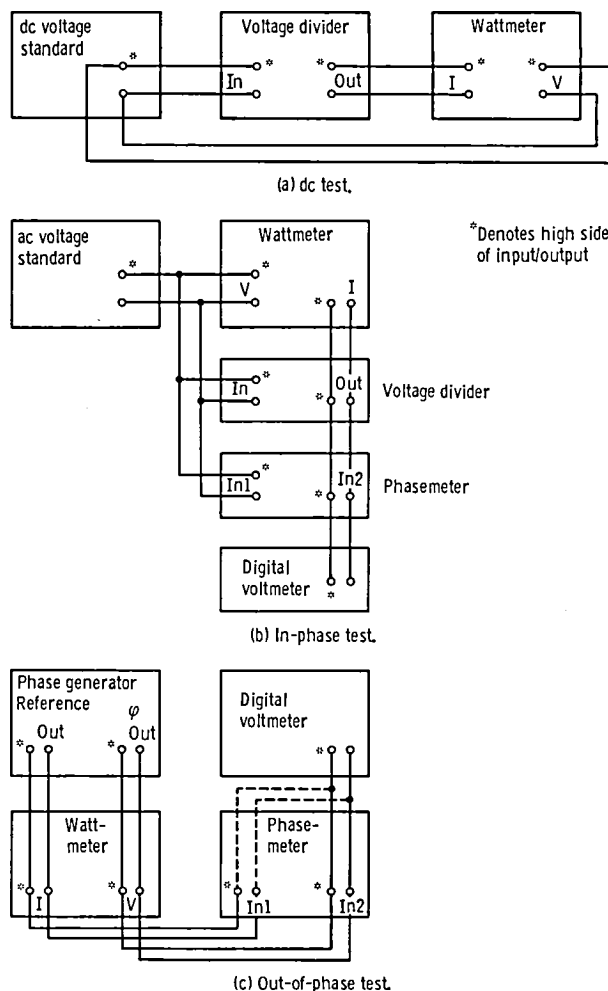


Figure 5. - Wattmeter calibration equipment and connection block diagrams.

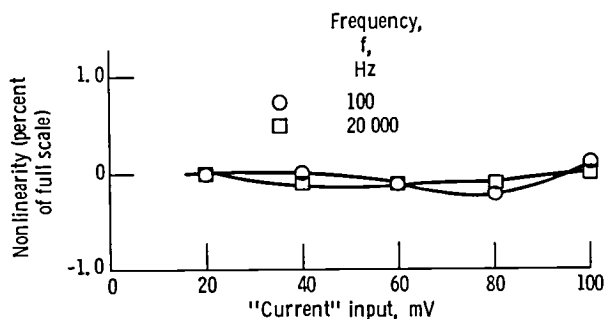


Figure 6. - Typical data for wattmeter linearity calibration at 100 hertz and 20 kilohertz, plotted as percent deviation from zero to full scale straight line versus current input magnitude at full scale voltage input $V_1 = 20 V_{rms}$.

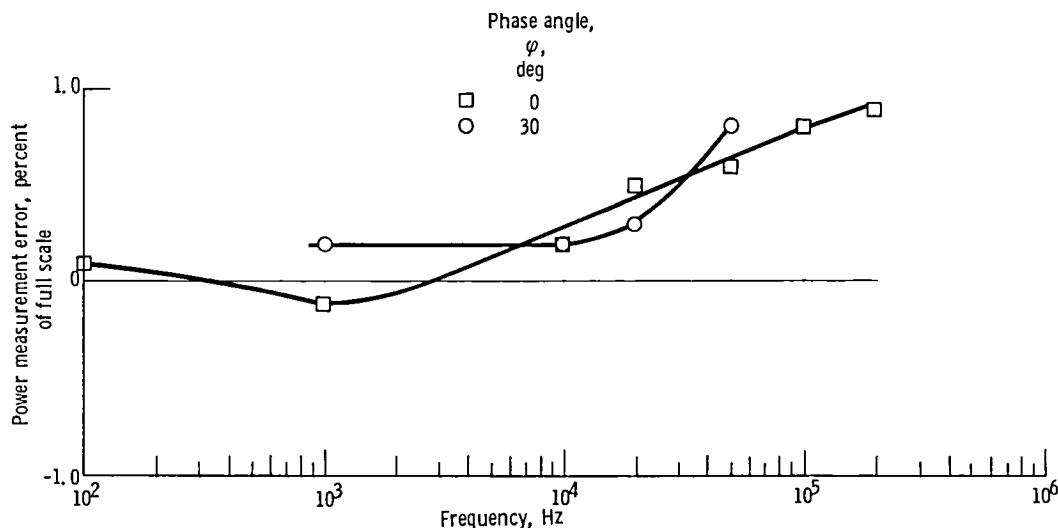


Figure 7. - Typical data showing power measurement error at 0° and 30° phase angles as a function of frequency.

shown in figure 7 are limited to frequencies less than 50 kilohertz by the digital phase angle generator which was selected for its separate variable outputs and its ease of use. From data of this type, a wattmeter's bandwidth can be determined for a desired accuracy over the range of input phase angles.

Complete testing of all wattmeter ranges is advised to characterize a wattmeter. Testing at selected frequencies and phase angles may be sufficient to recheck calibration and in calibrating additional wattmeters of the same model type.

The same equipment connections shown in figure 5 can be used for calibrating the other meter functions on those wattmeters which can also measure input voltage and current shunt voltage.

Determining Wattmeter Requirements

A typical application where a wideband wattmeter might be needed for accurate power measurement is shown in figure 8, a chopper-driven dc motor. This system will be referred to later in this section in power measurement examples. (Note that in the figure, measurement parameter polarities are in some cases opposite to the normal current flows, resulting in negative magnitudes for some parameters.) Maisel (ref. 2) analyzed the meter bandwidth required for a model of this system with some nominal parameters and determined the Fourier harmonics required to achieve power measurements with errors of less than 1 percent, for varying chopper duty cycle and motor back emf. Maisel's analysis assumed zero switching times and therefore would tend to predict higher

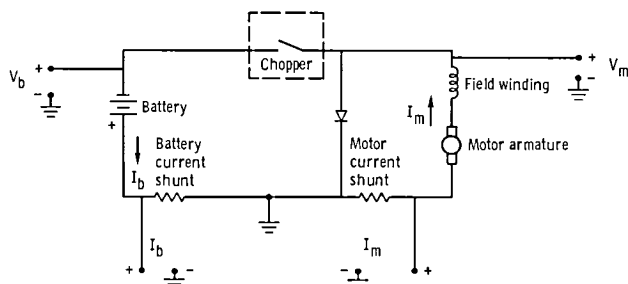


Figure 8. - Simplified schematic of chopper-driven dc motor.

bandwidth requirements than would actually be needed in real systems.

Linear system modelling is both approximate and time consuming when applied to real systems. It would be of benefit to many test engineers if an instrument and associated test techniques were available to use on wideband power systems to define wattmeter requirements. In this section, we will describe and illustrate the use of a calculating digital oscilloscope, with Fourier transform capabilities, to analyze significant power bandwidth in chopper systems.

Average power is the summation of all $V_k^* I_k$ terms for all of the spectral components of $v(t)$ and $i(t)$. V_k and I_k are the complex Fourier magnitudes, and $*$ denotes taking the complex conjugate. (Phase information is contained in the complex format.)

The cross-power spectral density of two periodic waveforms of the same period is

$$P_{xy}(\omega) = 2\pi \sum_{k=-\infty}^{\infty} Y_k^* X_k \delta(\omega - k\omega_1)$$

The real part of $Y_k^* X_k$ versus frequency is the spectrum of components comprising average power when $Y_k = V_k$ and $X_k = I_k$. An instrument which can generate cross-power spectrum, $Y_T^*(f) \cdot X_T(f)$, where $Y_T(f)$ and $X_T(f)$ are the Fourier transforms of $y(t)$ and $x(t)$ over the time period T , can therefore determine the average power contribution of each spectral component of a periodic waveform.

Visual display of the cross-power spectrum enables the test engineer to quickly determine the highest spectral component required for the accuracy desired.

A commercial instrument previously discussed as a digital wattmeter can function as a Fourier transform calculator. The calculating digital oscilloscope has preprogrammed function keys which can operate on stored data samples and can generate spectral data. The spectral resolution is $1/Nt_s$, where N is the number of data samples and t_s is the time interval between samples. The full scale frequency is $1/(2t_s)$.

In the remainder of this section, several examples of analyses for simulated and real chopper systems will be presented. The purpose for detailing these examples is not to present specific data but to illustrate the technique and to provide insight into the results to be expected in similar applications.

Example 1

The idealized simulation presented in Example 1 is a wideband, "resistive-load" application. The voltage and current waveforms for this simulation were generated with a dual output pulse generator. Since the two outputs are opposite in polarity, the generated "load" voltage is opposite from the conventional polarity for a positive current through a resistive load, resulting in a negative power magnitude. Figure 9(a) shows the system waveforms: trace A is load current, on/off with a duty cycle of 17 percent at a chopping rate of 1992 hertz (These data were obtained at a 500-kilohertz sampling rate); trace B is load voltage; trace C is instantaneous power, calculated as $A \times B$. Average power is calculated by the instrument to be -14.5 watts after an appropriate amperes-per-volt scale factor is used to convert trace A's millivoltage input to equivalent amperes. Keyboard commands can be used to generate rms voltage and current, and waveform integration commands give average voltage and current:

$$V_{rms} = 6.49 \text{ V}$$

$$I_{rms} = 2.24 \text{ A}$$

$$V_{ave} = -2.66 \text{ V}$$

$$I_{ave} = 0.988 \text{ A}$$

From these values, several results can be determined. The dc power is average voltage times average current, or -2.6 watts. The ac power is therefore $-14.5 - (-2.6) = -11.9$ watts. V_{rms} times I_{rms} equals 14.5 volt-amperes, which verifies that the "load" is resistive.

The simulated waveforms were then resampled at a rate of 50 kilohertz for purposes of spectral analysis. Fourier transforms of voltage and current were taken by keyboard command and then the cross-power spectrum was obtained as shown in figure 9(b), where only the positive, nonzero frequency components are displayed. The trace showing the real part of the cross-power spectrum is expanded for easier viewing. Each data point is separated by 2 kilohertz and range from the fundamental at 2 kilohertz to the rightmost harmonic at 24 kilohertz. From these data, table III was generated by doubling the positive frequency magnitudes to show the average power in each harmonic and the total ac power in those harmonic components. The total ac power shown in the table covers spectral components to 24 kilohertz. (The accuracy of the Fourier transformation is not being tested here, since the goal is to obtain enough quantitative spectral information to determine the required wattmeter bandwidth.)

Since 1 percent of the total average power is -0.14 watt, it can be seen that even the highest harmonics shown in table III collectively contribute significantly to the power if accuracies on the order of 1 percent are desired.

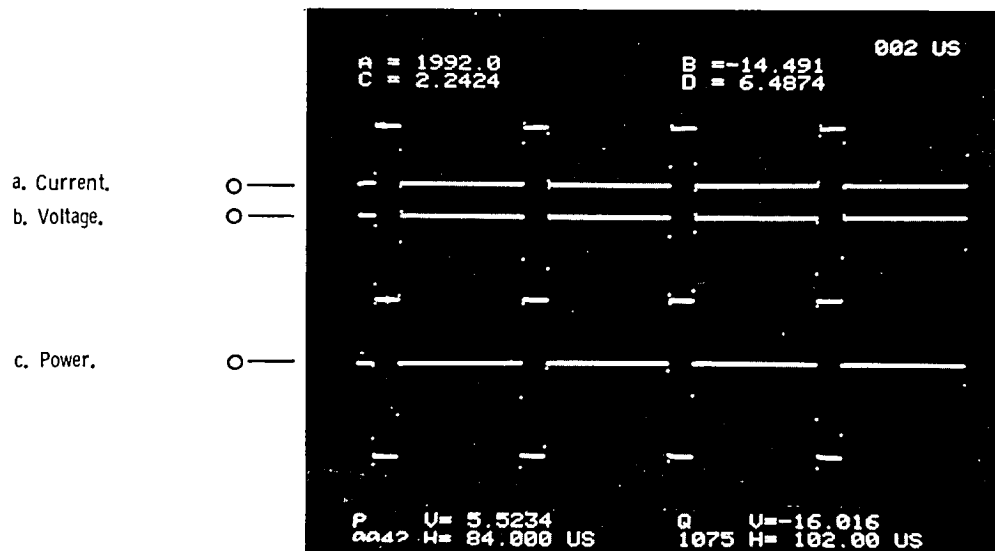
The imaginary cross-power spectral components were also summed; their total was only -0.2 volt-ampere. This result is consistent with a (simulated) resistive load.

A subsequent spectral analysis at 100 kilohertz sampling (50 kHz full scale) revealed power components of as much as 0.05 watt to the sixteenth harmonic (32 kHz).

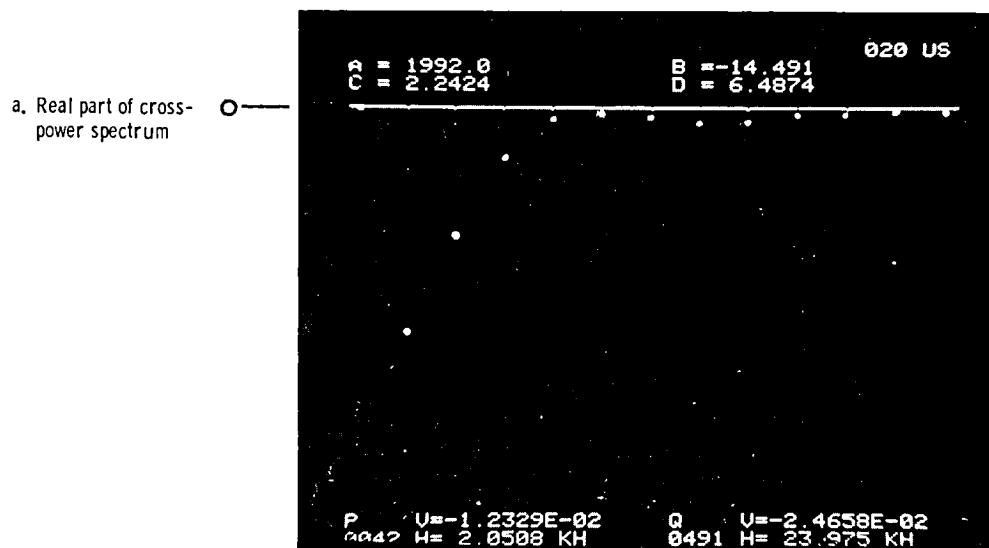
(For a purely resistive load, the relative power spectrum can be obtained from the square of the Fourier transform of either the voltage or current waveform, since they are related by only the scalar R .)

Example 2

Example 2 is also of a simulated system; but the waveforms approximate a dc motor application. Again the use of a dual output generator to provide the waveforms resulted in a negative voltage polarity and a corresponding negative power. Figure 10 shows the current, voltage, and power waveforms. Trace a is motor current and reflects time constants found with inductive loads. Trace b is motor voltage and



(a) Current, voltage, and calculated instantaneous power.



(b) Real part of complex cross-power spectrum of current and voltage.

Figure 9. - Sampled waveforms for example 1, a resistive load simulation.

TABLE III. – AVERAGE POWER
FOR EACH ac FOURIER
COMPONENT IN EXAMPLE 1

Harmonic	Analyzer frequency, kHz	ac power, W
1	2.002	-4.56
2	4.004	-3.38
3	6.006	-1.92
4	8.008	-.764
5	10.01	-.148
6	11.96	-.024
7	14.01	-.148
8	16.02	-.222
9	18.02	-.222
10	20.02	-.099
11	21.97	-.074
12	23.98	-.050
Total ac power		-11.62

trace c is calculated instantaneous load power. The frequency of chopping is 2015 hertz. The sampling rate is 200 kilohertz. The voltage, current, and power calculations of interest are

$$V_{ave} = -5.01 \text{ V}$$

$$I_{ave} = 1.86 \text{ A}$$

$$V_{rms} = 8.06 \text{ V}$$

$$I_{rms} = 2.24 \text{ A}$$

$$P_{ave} = -14.4 \text{ W}$$

Since the dc power calculates to be -9.31 watts, the ac power is -5.1 watts. Also, V_{rms} times I_{rms} is 18.1 volt-amperes, indicating a phase angle greater than zero at one or more of the ac power spectral components. Table IV shows the spectral analytical results, both real and imaginary, together with calculated phase angle. Here, since 1 percent of average power is -0.14 watt, there is no significant power beyond the second harmonic, or 4 kilohertz. This result is due to the relatively low bandwidth current waveform, and to the large dc power component.

The discrepancy between the waveform calculated ac power of -5.1 watts and the spectrum-derived power of -4.8 watts is a typical demonstration of the instrument limitations in accurately analyzing frequency spectra. The spectrum analysis techniques described in this report are presented only as methods to define power bandwidth and not as alternate techniques for accurately measuring power.

The next two examples were obtained from data on an actual chopper-driven dc motor system.

Example 3

Figure 11(a) shows the battery waveforms obtained during a 400-hertz chopper-driven dc motor test. Figure 8 shows the system and defines the polarities of the measurement parameters. (Although actual powers in kilowatts were involved, scale factors used in the data handling were the same as those used in the simulations; hence the current and power

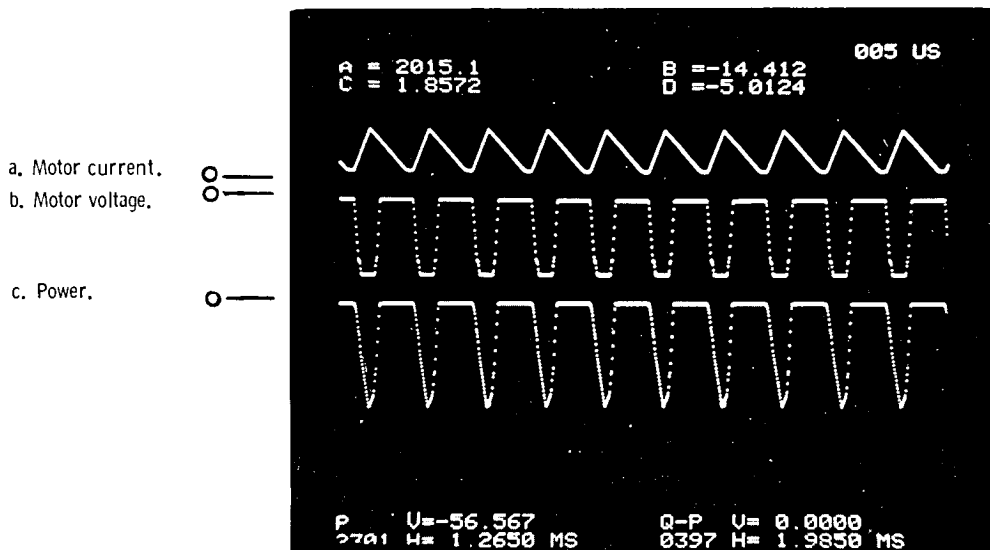
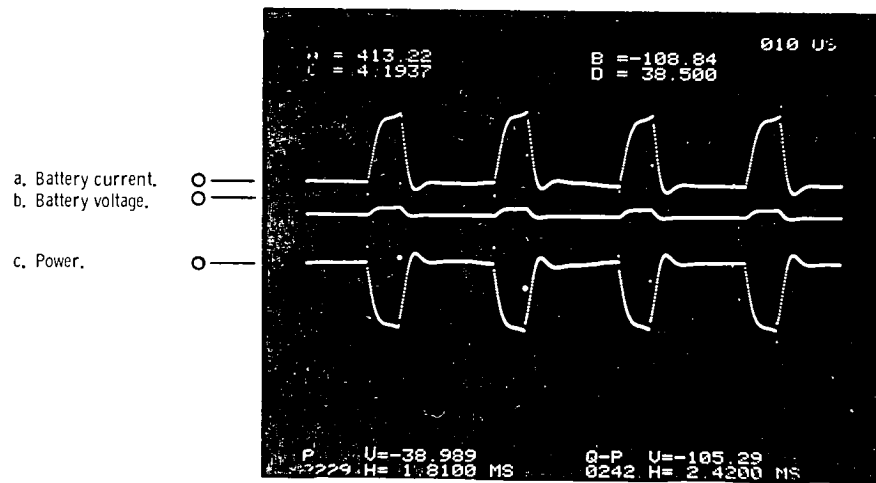


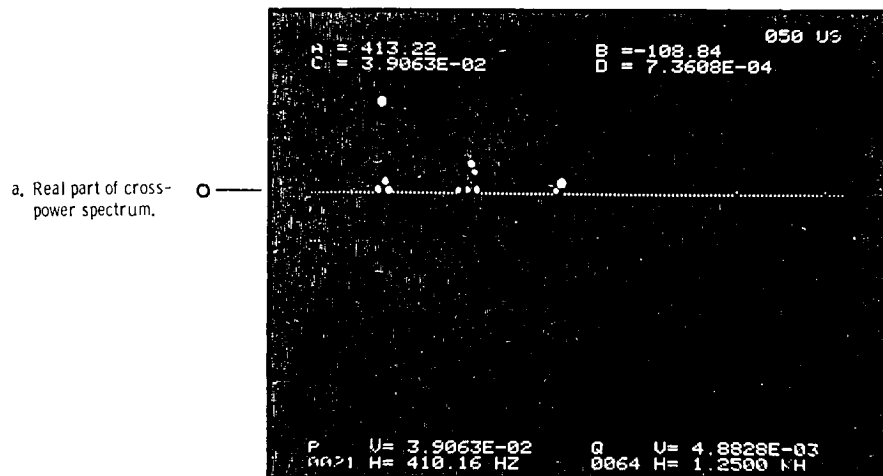
Figure 10. - Sampled waveforms for example 2, a dc motor simulation, showing motor current and calculated instantaneous power.

TABLE IV. - COMPLEX ac CROSS-POWER
SPECTRAL COMPONENTS FOR
EXAMPLE 2

Harmonic	Real cross power (average power), W	Imaginary cross power, V-A	Phase angle, θ_i , deg
1	-4.16	5.01	130
2	-0.69	.15	168
3	.01	-.01	-45
4	----	-.02	-90
5	----	-.01	-90
6	----	.01	90
	-4.84	5.13	---



(a) Battery current and voltage waveforms and calculated instantaneous power.



(b) Cross-power spectrum for typical chopper-driven dc motor.

Figure 11. - Sampled waveforms for example 3.

readings are only proportionally correct.) The key points to be noted for this example are that, in spite of the 30 percent duty cycle, over 80 percent of the battery power withdrawn is dc power, and that the ac power is opposite in sign to the dc power.

Trace a shows the battery current and trace b shows the battery voltage which decreases in magnitude when current is drawn. Trace c is the calculated instantaneous power.

The average power was calculated from the waveforms to be -50.9 watts. The dc power was calculated to be -59.8 watts. The expected ac power is 8.9 watts.

The real part of the cross-power spectrum is shown in figure 11(b). (The broadening of each harmonic component into more than one frequency interval is due primarily to limitations in the filter calculations used in the discrete Fourier transformation; the frequency lines related to each harmonic are summed to give the magnitude at that harmonic.) The harmonic powers can be summarized as: 4.5 watts at the fundamental; 2.5 watts at the second harmonic; and 0.5 watt at the third harmonic; totaling to 7.5 watts of ac power. (The discrepancy between 7.5 and 8.9 W is not negligible, but the spectral data were obtained minutes after the average power waveforms. The system operating characteristics could not be held unvarying over this period of time. Since we were interested in general characteristics and relative spectral components, repeatability in operating point selection was not stressed.) The imaginary part of the cross-power spectrum was zero; therefore, the power factor for the load on the battery was unity.

Example 4

Example 4 illustrates actual dc motor power waveforms (see fig. 12). Refer again to figure 8 for definitions of the system parameters. Trace a is motor current; trace b is motor voltage; and trace c is calculated instantaneous power. The average power, from the waveforms, is 104.7 watts. The dc power is 96.8 watts, with an expected ac power of 7.9 watts. The harmonic powers determined from the real part of the cross-power spectrum are: 6.6 watts at the fundamental and 0.4 watt at the second harmonic for a total ac power of 7.0 watts. The imaginary cross-power spectral magnitude totalled -9.1 volt-ampere, resulting in a power factor of about 0.6 for the motor load. This contrasts with the power factor for Example 3, of battery power, which was about 1.

Battery and motor power data were taken at a total of five operating points. Figure 13 plots the ac power contribution to total power as a function of chopper duty cycle. Even though the battery waveform spectra were of wider bandwidth than those for motor power, the total ac power in both parts of the system were approximately the same for a given duty cycle.

Although no conclusive results can be drawn from the data on one system, this potential functional relationship between ac power contribution and duty cycle could be used to predict power measurement errors for those cases where a curve can be established for the system. This information, together with bandwidth-duty cycle correlations, could be used to predict wattmeter errors over the full operating range of the chopper.

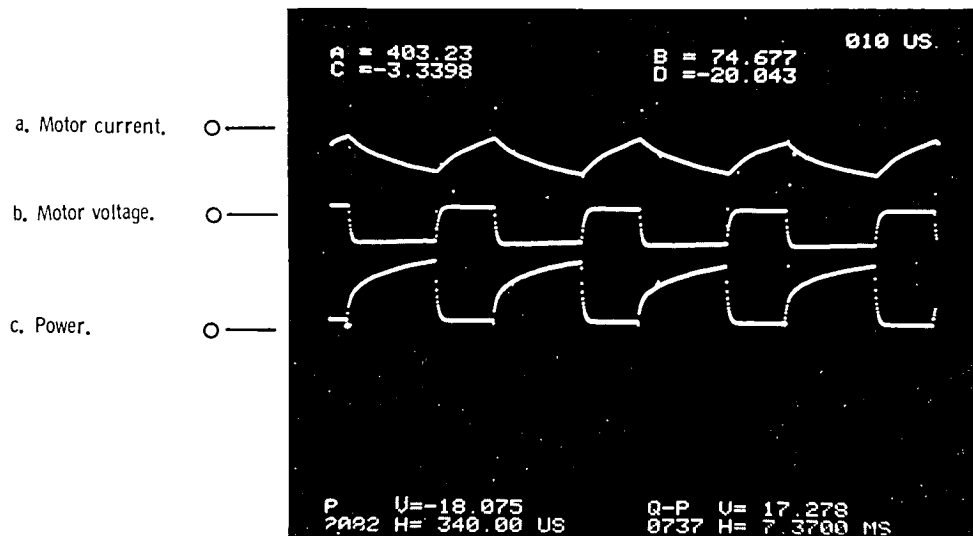


Figure 12. - Sampled waveforms for example 4, motor current and voltage and calculated instantaneous power for typical chopper-driven dc motor.

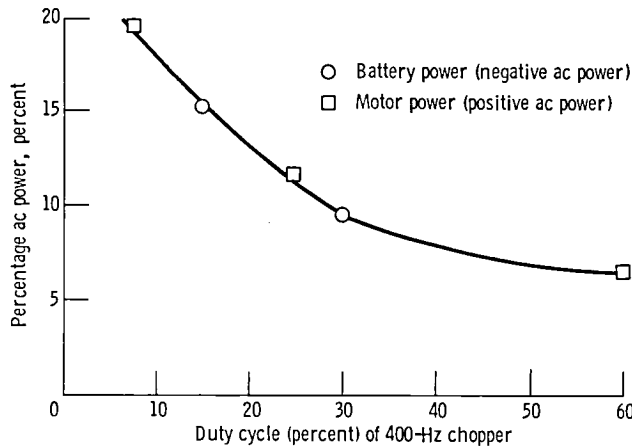


Figure 13. - Percentage of total power for battery output and dc motor load delivered as ac power in typical chopper-driven system.

Concluding Remarks

A careful review of the power measurement requirements for an inverter or chopper application is very important to the selection of optimum instrumentation in terms of performance versus cost. Waveform analysis, even in an approximate form, can be used to obtain valuable results for determining power meter specifications. But calibration and evaluation of the chosen wattmeter is required before confidence in the power readings can be attained. Agreement of measurements obtained with two

different techniques of instrumentation will also aid in establishing confidence.

This report describes straightforward engineering techniques for a new application. The primary conclusions to be drawn are as follows:

1. Electronic wattmeters capable of measuring power in switching circuit applications are available.

2. Analytical instruments can be used to determine the power bandwidth requirements.

3. Power measurement is sensitive to phase shifts in the current and voltage signals, and this sensitivity increases as power factor decreases. Matching of the phase shifts can eliminate these errors, but the matching must include the current transducers and the signal conditioning electronics in both the current and voltage channels.

4. Calibration of wideband wattmeters using variable frequency, variable phase sine waveforms is the only NBS-traceable method available. This type of calibration data can be used to define meter bandwidth as a function of input power factor and can be used as a basis for comparison of wattmeters.

5. Current shunt selection and calibration is an important factor in achieving accurate power measurement.

In addition to wattmeter selection and usage, the careful engineering practices recommended for any low level signal measurement apply to current shunt signals. A coaxial shunt may have less resistance than a foot-long piece of current conducting cable. Therefore placement of the signal common is very critical to accurate measurement, especially when a single ended wattmeter is used.

Appendix—A Channel Mismatch Parameter for a Wattmeter Model

In this appendix, we will develop an approximate model of an analog multiplier-based wattmeter (similar to Maisel's (ref. 2) model) for the purpose of defining a parameter of mismatch between the current and voltage channels. This parameter can be determined from calibration data and the resulting model can be used to predict input frequency-sensitive wattmeter errors. Intermediate equations in the development of the simple model can be chosen as a more detailed model if the frequency parameters of the wattmeter under test have been defined. The derivation was done in the frequency domain to facilitate extensions or modifications to the model for higher order system functions or nonsinusoidal inputs.

The wattmeter model will be defined by the following equation:

$$V_o = V_1 I_1 \cos(\varphi_1 + 2\pi f_1 t_d) \quad (A1)$$

where

V_o output power reading for a sinusoidal input at frequency f_1

V_1 rms voltage

I_1 rms current

φ_1 phase angle between voltage and current

f_1 input frequency

t_d mismatch parameter

Figure 14 shows the wattmeter transfer function block diagram. All transfer functions are assumed linear except for the multiplier. The multiplier is assumed to be ideal. Convolution in $H_3(\omega)$ is defined by

$$\begin{aligned} & \frac{1}{2\pi} V_1(\omega) H_1(\omega) \otimes V_2(\omega) H_2(\omega) \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} V_1(x) H_1(x) V_2(\omega - x) H_2(\omega - x) dx \quad (A2) \end{aligned}$$

where $\omega = 2\pi f$. For our sinusoidal analysis, let

$$v_1(t) = V_p \cos \omega_1 t \quad (A3)$$

$$v_2(t) = I_p \cos(\omega_1 t + \varphi_1) \quad (A4)$$

Also, for simplification of the model, let $H_1(\omega)$, $H_2(\omega)$, and $H_4(\omega)$ be described by first order low pass transfer functions, where H_1 and H_2 are due to amplifier roll off and H_4 is the filtering action which generates an average power signal. Then,

$$H_1(\omega) = \frac{1}{1 + (j\omega/\omega_a)} \quad (A5)$$

$$H_2(\omega) = \frac{1}{1 + (j\omega/\omega_b)} \quad (A6)$$

$$H_4(\omega) = \frac{1}{1 + (j\omega/\omega_c)} \quad (A7)$$

where $j = \sqrt{-1}$, and ω_a , ω_b , and ω_c are the corner frequencies for the three transfer functions. The convolution output $V_o'(\omega)$ for sinusoidal inputs becomes

$$\begin{aligned} V_o'(\omega) = & \frac{\pi V_p I_p}{2} \left(\delta(\omega) \left\{ \frac{\omega_a \omega_b [\omega_a \omega_b + \omega_1^2 - j\omega_1(\omega_b - \omega_a)] e^{-j\varphi_1} + \omega_a \omega_b [\omega_a \omega_b + \omega_1^2 + j\omega_1(\omega_b - \omega_a)] e^{j\varphi_1}}{(\omega_a \omega_b + \omega_1^2)^2 + \omega_1^2 (\omega_b - \omega_a)^2} \right\} \right. \\ & \left. + \delta(\omega - 2\omega_1) \left[\frac{\omega_a \omega_b e^{j\varphi_1}}{\omega_a \omega_b + j\omega_1(\omega_a + \omega_b) - \omega_1^2} \right] + \delta(\omega + 2\omega_1) \left[\frac{\omega_a \omega_b e^{-j\varphi_1}}{\omega_a \omega_b - j\omega_1(\omega_a + \omega_b) - \omega_1^2} \right] \right) \quad (A8) \end{aligned}$$

where $\delta(x)$ is the delta function. If the filter cutoff frequency $\omega_c \ll \omega_1$, the average power as measured by the meter is $1/2\pi$ times the coefficient of the $\delta(\omega)$ term. Further simplification yields

$$V_o = \frac{V_p I_p}{2} \left[\frac{(\omega_a^2 \omega_b^2 + \omega_a \omega_b \omega_1^2) \cos \varphi_1 + \omega_1 \omega_a \omega_b (\omega_a - \omega_b) \sin \varphi_1}{\omega_a^2 \omega_b^2 + \omega_1^4 + \omega_1^2 (\omega_a^2 + \omega_b^2)} \right] \quad (A9)$$

If $\omega_a = \omega_b$ (perfectly matched channels), the $\sin \varphi$ term will be zero. If, also, $\omega_1 \ll \omega_a$, then $V_o = (V_p I_p \cos \varphi_1)/2$, which is the true average power. For real wattmeters, however, $\omega_a \neq \omega_b$. We want to show that for $\omega_a \neq \omega_b$, and for $\omega_1 < 0.2 \omega_a$, the angle correction can be approximated by treating the channel mismatch as a pure time delay added to the input phase shift, as $\cos(\varphi_1 + 2\pi f_1 t_d)$. Let $\omega_1 \ll \omega_a$ and $\omega_1 \ll \omega_b$. Then

$$V_o \cong \frac{V_p I_p}{2} \left[\cos \varphi_1 + \frac{\omega_1 (\omega_a - \omega_b)}{\omega_a \omega_b} \sin \varphi_1 \right] \quad (A10)$$

Since for y small, $\cos(x+y) \cong \cos x - y \sin x$; then

$$\cos(\varphi_1 + \omega_1 t_d) \cong \cos \varphi_1 - \omega_1 t_d \sin \varphi_1 \quad (A11)$$

If we set $-\omega_1 t_d = \omega_1 (\omega_a - \omega_b) / \omega_a \omega_b$,

$$t_d = \frac{\omega_b - \omega_a}{\omega_a \omega_b} \quad (A12)$$

In another form, where $\tau_a = 1/\omega_a$ and $\tau_b = 1/\omega_b$, $t_d = \tau_a - \tau_b$. Therefore,

$$V_o \cong \frac{V_p I_p}{2} \cos [\varphi_1 + \omega_1 (\tau_a - \tau_b)] \quad (A13)$$

or

$$V_o = V_1 I_1 \cos(\varphi_1 + 2\pi f_1 t_d) \quad (A1)$$

To determine t_d for a given wattmeter, inputs at ω_1 are applied for large phase angles φ_1 , and ω_1 is increased until a significant error in measured power factor (apparent phase angle) occurs. Then t_d can be calculated from the difference between the actual input phase angle and the apparent phase angle. Repeatability of results for different frequencies and phase angles will verify the validity of equation (A1) for the wattmeter. To ensure that the measurement errors are not due to magnitude rolloff, inputs at 0° phase should be applied for the chosen ω_1 's and the output checked for flatness for frequencies in this range (since the sensitivity of V_o to $\omega_1 t_d$ will be a minimum at $\varphi_1 = 0^\circ$). Wattmeter errors due to channel mismatch can then be calculated for any angle φ_1 and for any ω_1 , where $\omega_1 \ll \omega_a$ and $\omega_1 \ll \omega_b$.

The parameter t_d was determined for several available electronic wattmeters. The values obtained ranged from 0.01 to 0.25 microsecond. In all cases the first order wattmeter model resulted in reasonably consistent data and a value for t_d which could be used to determine approximate errors over a wide range of frequencies and phase angles.

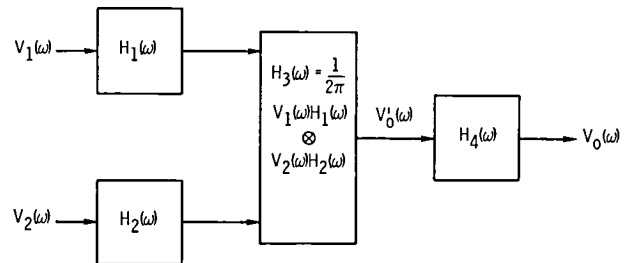


Figure 14. - Transfer functions for model of electronic wattmeter.

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1. Report No. NASA TM-81545		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle SPECIFYING AND CALIBRATING INSTRUMENTATIONS FOR WIDEBAND ELECTRIC POWER MEASUREMENTS				5. Report Date December 1980	
				6. Performing Organization Code 778-36-06	
7. Author(s) Daniel J. Lesco and Donald H. Weikle				8. Performing Organization Report No. E-498	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				10. Work Unit No.	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Transportation Programs Washington, D.C. 20545				13. Type of Report and Period Covered Technical Memorandum	
				14. Sponsoring Agency Code Report No. DOE/NASA/1044-8	
15. Supplementary Notes Prepared under Interagency Agreement EC-77-A-31-1044.					
16. Abstract The wideband electric power measurement related topics of electronic wattmeter calibration and specification are discussed. Tested calibration techniques are described in detail. Analytical methods used to determine the bandwidth requirements of instrumentation for switching circuit waveforms are presented and illustrated with examples from electric vehicle type applications. Analog multiplier wattmeters, digital wattmeters, and calculating digital oscilloscopes are compared. The paper describes the instrumentation characteristics which are critical to accurate wideband power measurement.					
17. Key Words (Suggested by Author(s)) Electrical power measurement High frequency wattmeter				18. Distribution Statement Unclassified - unlimited STAR Category 35 DOE Category UC-96	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 17	
				22. Price* A02	

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